BROADBAND PHOTOREFRACTIVE DEVICE USING AN ASYMMETRIC COUPLED QUANTUM WELL STRUCTURE

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Abstract

We propose a new approach to expand the diffraction spectral bandwidth of photorefractive quantum well devices by employing asymmetric coupled quantum well (ACQW) structures. We fabricate a designed AlGaAs/GaAs ACQW photorefractive *p-i-n* diode and demonstrate broadband diffraction in the longitudinal Stark geometry. The diffraction is observed at a spectral region of over 30 nm, which is about three times wider than the spectral range where the diffraction occurs in a conventional photorefractive quantum well structure.

1.Introduction

Dynamic processing of femtosecond pulses has attracted increasing attention for the implementation of high bit-rate optical communication, controlling chemical reactions, and so on. Highly sensitive fast optically addressed spatial light modulators (OASLM's) are key elements in pulse processing systems. Photorefractive multiple quantum well (PR-MQW) devices[1] are promising candidates for such OASLM's because they have high sensitivity and fast response by combining large excitonic electro-optic effects and large carrier mobilities. Using PR-MQW devices, some kinds of dynamic manipulations of optical pulses have been demonstrated.[2-4] However, the PR-MQW devices still have some problems. One of important problems of the PR-MQW device in such applications is its relatively narrow diffraction bandwidth. Excitonic resonant electro-optic effects limit the sensitivity to a narrow spectral range (typically ~5 nm) around the excitonic resonant wavelength although they enhance the photorefractive effect.

So far, two approaches have been proposed in order to realize broadband PR-MQW devices in the Franz-Keldysh geometry[1], where an electric field is applied parallel to the MQW layers. One approach is using Fibonacci superlattice structures.[5] The other is dividing the MQW structure into several substructures that have slightly different excitonic transition wavelengths.[6] Using the latter approach, the diffraction bandwidth has been broadened up to 8.3 nm.

The longitudinal Stark geometry is another configuration of PR-MQW devices. A PR-MQW device in this geometry consists of an electro-optic MQW layer sandwiched by two high resistive cladding layers. Devices are operated by applying an electric field perpendicularly to the MQW layer. An illumination of spatially non-uniformed intensity pattern forms photorefractive gratings through dynamic screening of the applied field. Photo-excited carriers are driven to the MQW/clad interfaces, and are trapped at these interfaces and cladding layers. Consequently, the applied field is screened at bright regions, and a spatial modulation of the internal field is generated. This is transferred to the photorefractive gratings through electroabsorption and electrorefraction effects. Compared with devices in the Franz-Keldysh geometry, larger optical nonlinearities can be obtained with a smaller operating voltage in the longitudinal Stark geometry. In addition, devices with larger active areas can be fabricated.

Here we propose and demonstrate a new approach to expand the diffraction bandwidth of the PR-MQW device in the longitudinal Stark geometry by employing asymmetric coupled quantum well (ACQW) structures.

2. ACQW structure for broadband PR-MQW device

In ACQW structures, two (or more) different quantum wells are coupled by thin coupling layers. ACQW structures have several attractive features for applications to PR-MQW devices. They are more sensitive to an applied field than conventional rectangular quantum well (RQW) structures. Linear electroabsorption effect has been demonstrated in a semi-insulating AlGaAs/GaAs ACQW structure.[7] In addition, excitonic resonant energies can be easily controlled by changing the coupling strength between quantum wells. This enables one to tailor the electro-optic spectrum and expand the diffraction bandwidth.

Figure 1 illustrates an ACQW structure and wavefunctions of the electron ground state (e1) and the heavy-hole first excited state (hh2). When an electric field, which is parallel to the growth direction, is applied to the structure, the quantum confined Stark effect and the field-induced oscillator-strength change cause the electroabsorption in the ACQW structure. The applied field tends to localize wavefunctions of e1 and hh2 at the same well as shown in Fig. 1. This localization increases the oscillator strength of the e1-hh2 transition, which is weak without the applied field.

Figure 2 shows calculated excitonic transition energies of e1-hh1, e1-hh2, e2-hh1, and e2-hh2 transitions as a function of the applied field. The applied field decreases the resonant energy of the e1-hh1 transition and weakens its strength. Simultaneously, the field shifts the e1-hh2 transition toward the high-energy side and enhances its absorption. This induces the electro-optic effect at a broad spectral range. In addition, ACQW structures can be designed so that e2-related excitons are close to e1-excitons in energy and contribute to the further broadening of the electro-optic and diffraction spectra. In this structure, the e2-excitons increase the absorption at around 1.52 eV, whereas they reduce the absorption at around 1.54 eV as shown in Fig. 2. This enhances the diffraction efficiency at the high-energy side of its spectrum. Thus, diffraction occurs over a wide spectral region as shown below.

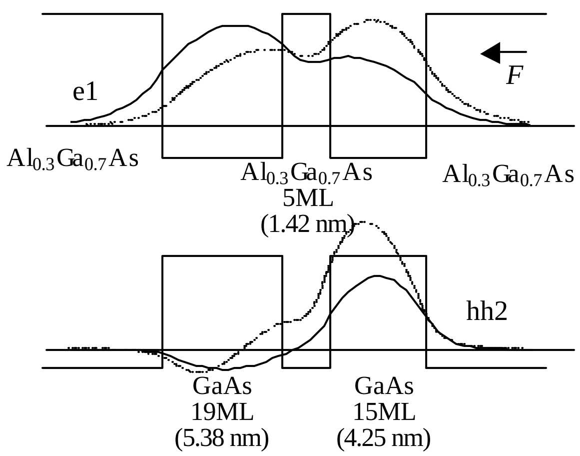

Fig. 1. An ACQW structure and wavefunctions of the electron ground state and the heavy-hole first excited state under zero-field (solid curves) and an applied field (dotted curves).

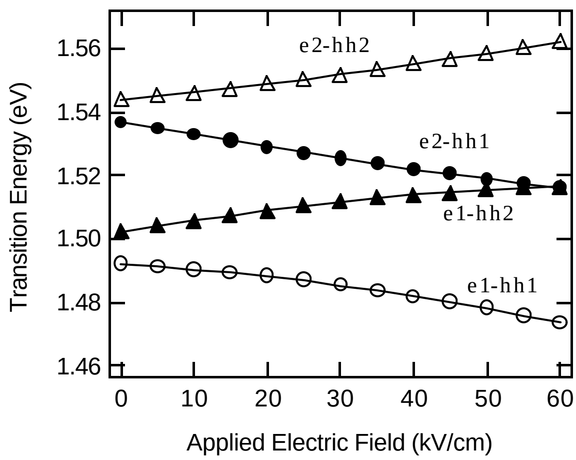

Fig. 2. Calculated excitonic transition energies as a function of the applied field. Open (closed) symbols indicate that the oscillator strength of the corresponding transition decreases (increases) with the increase of the applied field.

3. Experiments

The sample used here has a *p-i-n* structure and is grown on an n-GaAs substrate by molecular beam epitaxy. The *i*-region consists of an ACQW structure sandwiched between two 100-nm-thick low-temperature-grown (LTG) cladding layers. The ACQW structure is the same as that shown in Fig. 1, and is 61 periods of wider GaAs wells (5.38nm), $Al_{0.3}Ga_{0.7}As$ thin coupling layers (1.42 nm), narrower GaAs wells (4.25 nm), and $Al_{0.3}Ga_{0.7}As$ thick barriers (5.1 nm). The growth temperatures of the ACQW structure and LTG cladding layers are 500 C and 300 C, respectively. After the crystal growth, the sample is annealed at 600 C for 10 min in order to make the LTG layers semi-insulating. Finally, the substrate is removed by a selective etching technique because the GaAs substrate is opaque at interesting wavelengths. The transmission spectrum of the fabricated sample is shown in Fig. 3. Arrows indicate the calculated excitonic transition wavelengths. Predicted resonant wavelengths agree with our experimental result. A peak observed around 870 nm is due to the Fabry-Perot effect.

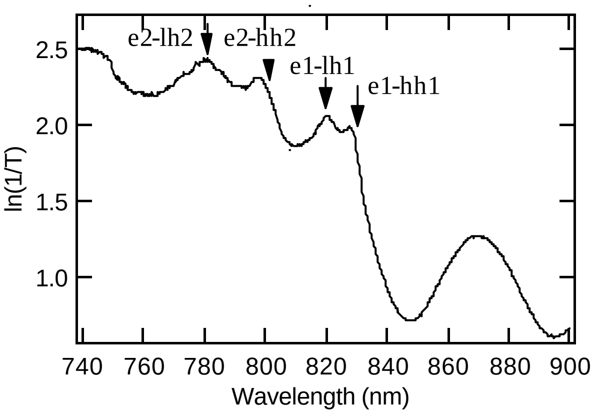

Fig. 3. Transmission spectrum of the designed ACQW *p-i-n* diode.

The sample is operated with a reverse voltage. The direction of an applied reverse voltage is from the narrower well to the wider one, as shown in Fig. 1. The obtained electroabsorption and elecrtorefraction spectra at an applied reverse voltage of 10 V are shown in Fig. 4. The electrorefraction spectrum is calculated from the electroabsorption through the Kramers-Kronig relation. A large electro-optic effect is observed at a spectral region over 40 nm. Using the theoretical expression of output diffraction efficiency[1], this result predicts that diffraction will occur over a 30-nm spectral range although a small dip is observed in its spectrum (see the solid curve in Fig. 5). For comparison, we fabricated another *p-i-n* diode with a RQW structure and measured the electroabsorption spectrum. This RQW structure has a well thickness of 9.63 nm, which is the same as the total well thickness in one period of the ACQW structure. The diffraction

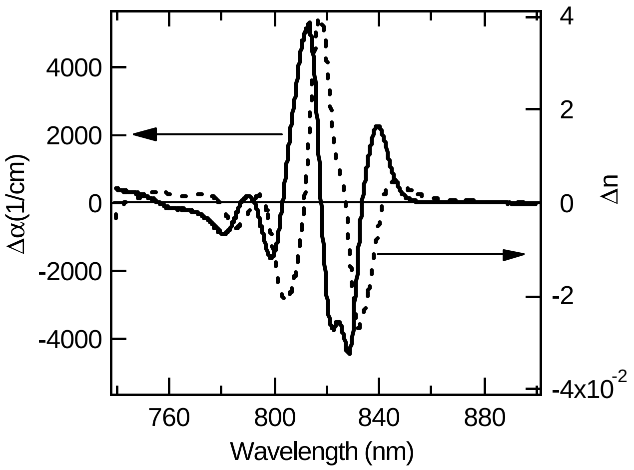

Fig. 4. Electroabsorption (solid curve) and electrorefraction (dashed curve) spectra of the PR-ACQW *p-i-n* diode. The applied reverse voltage is 10 V.

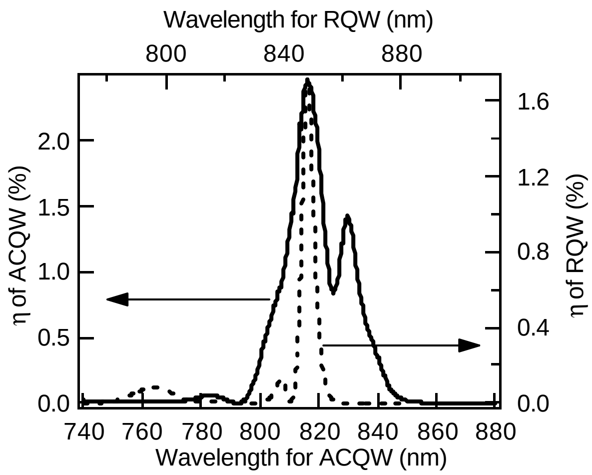

Fig. 5. Expected diffraction spectra of the ACQW (solid curve) and the RQW (dashed curve) structures at the applied voltage of 10 V.

spectrum of this RQW structure (the dashed curve in Fig. 5) is much narrower than that of the ACQW structure. In the RQW structure, large diffraction occurs only at a 10-nm spectral range.

We measured the diffraction efficiency of this PR-ACQW device in a degenerate four-wave mixing configuration[1]. The spectrum of measured diffraction efficiency is plotted in Fig. 6 along with the predicted one. In this measurement, a reverse voltage of 10 V is applied at a frequency of 95 Hz. The total incident intensity is 21 mW/cm^2, and the grating period is 40 μm. As predicted, the large diffraction has been observed at a spectral region over 30 nm. However, a maximum diffraction efficiency obtained in our experiment is only ~0.08%, which is ~30 times smaller than the expected one. Further optimizations of clad structures and their growth conditions will enhance the diffraction efficiency.

The broadband diffraction obtained in our experiment indicates that PR-ACQW devices will be quite useful in dynamic pulse-processing systems.

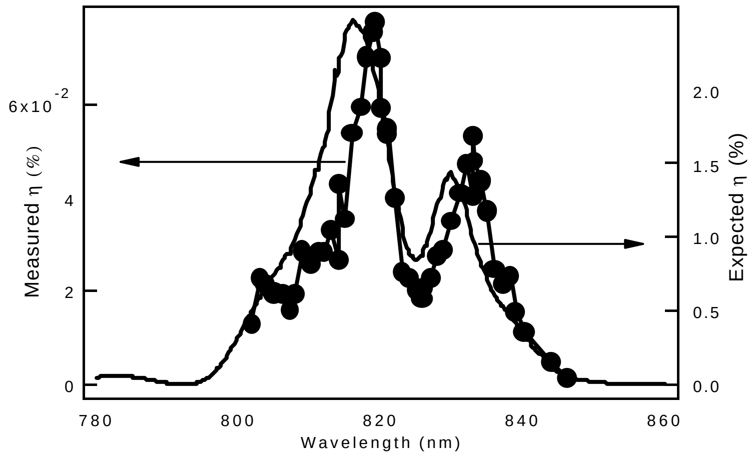

Fig. 6. Measured output diffraction efficiency and expected one as a function of wavelength. The applied reverse voltage is 10 V.

4. Conclusions

In conclusion, we have proposed PR-ACQW devices in order to achieve broadband diffraction, which is important in applications such as dynamic processing of femtosecond pulses. A broad diffraction bandwidth in the longitudinal Stark geometry has been demonstrated in an AlGaAs/GaAs PR-ACQW *p-i-n* diode. In a designed device, the diffraction has been observed over a 30-nm spectral region with a maximum output diffraction efficiency of ~0.08%. PR-ACQW devices will be suitable for pulse-processing applications

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